

A kinematic, Kevlar[®] suspension system for an ADR

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Abstract

The High Resolution Airborne Wideband Camera (HAWC) and the Submillimeter And Far Infrared Experiment (SAFIRE) will use identical Adiabatic Demagnetization Refrigerators (ADR) to cool their bolometer detectors to 200mK and 100mK, respectively. In order to minimize thermal loads on the salt pill, a Kevlar[®] suspension system is used to hold it in place. An innovative, kinematic suspension system is presented. The suspension system is unique in

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that it consists of two parts that can be assembled and tensioned offline, and later bolted onto the salt pill. The resulting assembly constrains each degree of freedom only once, yielding a kinematic, tensile structure.

Keywords: kinematic, Kevlar, suspension.

1. Introduction

The High-Resolution Airborne Wide-band Camera (HAWC)[1] and the Submillimeter And Far InfraRed Experiment (SAFIRE)[2] are both far-infrared astronomical instruments being built to study star formation, protoplanetary disks, and interstellar gas and dust. Both instruments are being built for the Stratospheric Observatory For Infrared Astronomy (SOFIA), an airplane-based telescope. Both will employ microcalorimeter bolometers developed at NASA's Goddard Space Flight Center (GSFC). HAWC and SAFIRE require the detectors to be cooled to 200mK and 100mK, respectively, but both will use Adiabatic Demagnetization Refrigerators (ADRs) as the final stage cooler. As the GSFC was making the ADR for both instruments, a single design that would work for both was pursued.

2. Some background: ADR's, Kevlar, and kinematic mounts

The HAWC ADR is shown in Figure 1. Before describing the design of this suspension system, some background on ADRs, Kevlar, and kinematic mounts will be presented.

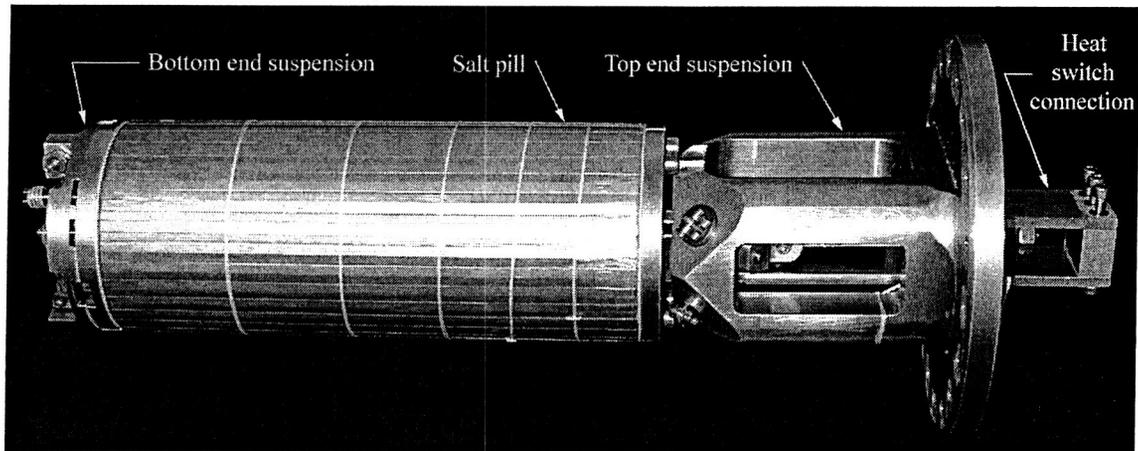


Figure 1: The HAWC ADR.

2.1 Adiabatic Demagnetization Refrigerators

For a full description of the thermal design of this ADR, please refer to Tuttle [3].

In brief, an ADR consists of a paramagnetic salt pill mounted in the core of a powerful electromagnet, and a heat switch for thermally connecting the salt pill to and disconnecting it from the helium bath as required.

The salt, in this case ferric ammonium alum, is typically grown from solution onto a matrix of gold wires inside a cylindrical container. The salt and its container are collectively called the “salt pill”.

When the magnet is energized, the magnetic moment of each iron atom aligns with the magnetic field, decreasing the magnetic entropy and increasing the temperature. At this point, the heat switch is closed, allowing the pumped liquid helium bath to cool the magnetized salt pill. SAFIRE and HAWC have a gas-gap heat switch, where a gas is either admitted into or removed from a narrow gap, enabling or preventing heat flow.

After the salt pill has cooled to the temperature of the bath, the heat switch is opened and the magnet is slowly de-energized. The magnetic moments in the salt are free to randomly reorient themselves, and the salt pill temperature drops well below the bath temperature. The detector is thermally anchored to the salt pill.

The mount between the salt pill and the enclosing helium tank and magnet is one of the ADR’s principle heat loads, so a mount design with a high thermal resistance will increase its hold time and thermal performance. Salt pill vibrations can be converted into heat, so it is also important that the mount be rigid. Additionally, salt pills are engineered more for thermal performance than as structural components, so the ideal mount should not put the pill into tension

or bending as part of its load path. The HAWC kinematic Kevlar suspension system meets the isolation, stiffness, and preloading requirements, and has several advantages over existing designs.

2.2 Kevlar

Kevlar has a very high ratio of stiffness to thermal conductivity at cryogenic temperatures. Kevlar fibers will only support a tensile load, in contrast to fiberglass epoxy, so a tensile structure must be used. Kevlar fibers are composed of highly ordered, rod-like polymer molecules. This gives them their tremendous stiffness – 3 times that of steel for the same weight. This property, however, causes the fibers to break easily around a sharp bend. The implication of this for any tensile structure using Kevlar is that it should avoid being knotted, and it has a minimum allowable bend radius. Typical solutions for attaching to the ends of Kevlar are gluing the ends of the fibers into drilled-out screws or similar fittings, or wrapping the fibers around pulleys, with capstans for tensioning. Another approach, used in this design, was to form the Kevlar fibers into a large loop, gluing the two ends together using Stycast epoxy. The loop was then twisted into a figure-8 and doubled back upon itself several times, forming a smaller diameter loop with a thicker cross-section, with all but a fraction of the fibers continuous. This loop was then strung between two .64 cm

(.250") diameter rollers, which formed the attachment points to the rest of the structure.

2.3 Kinematic mounts

A mount is said to be kinematic if it constrains each of the six possible degrees of freedom (DOF)(translation in X, Y, Z , rotation about X, Y, Z) exactly once.

Conceptually, the simplest way to build up a kinematic mount is to use six 1-degree of constraint (DOC) mounts (Figure 2), arranged so they complement each other and collectively lock out all 6 DOF. A 1-DOC mount can be made out of tensile elements, such as Kevlar rope (Figure 3). The rope cannot resist compression, yet this mount resists motion along the rope's length with the tensile modulus of the *rope* in *both* directions, as long as the applied load does not exceed the preload applied by the spring. To help envision this, imagine that the force from the preloading spring in Figure 3 stretches the rope segment on the right by a small amount. A force pushing the block to the right would first have to remove that strain, which occurs at the spring rate of the rope on the right. It also has to deflect the spring on the left the same amount, but presumably the spring has a much lower spring rate than the rope and its contribution is negligible.

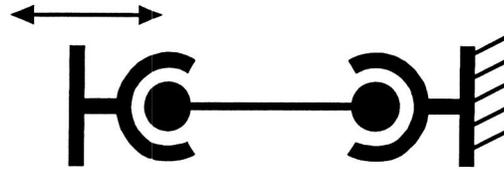


Figure 2: A 1-DOC mount made up of two ball joints. Relative motion between the bases is allowed in all degrees of freedom except along the axis of the connecting link.

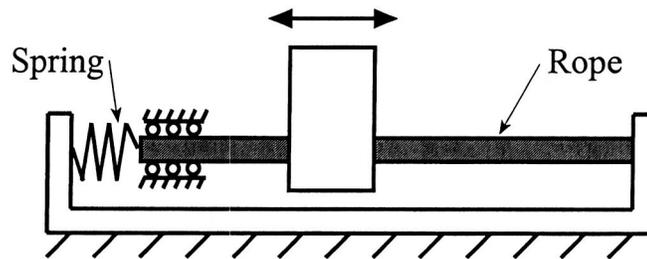


Figure 3: A 1-DOC tensile mount. The arrows indicate the direction of constraint.

Deflections orthogonal to the direction of constraint only stretch the rope a small amount (compared to the deflection distance), so the perceived stiffness of the mount in those directions is much smaller. Transverse directions are therefore considered degrees of freedom, for small motions.

Figure 4 shows a 3-2-1 kinematic mount. The three constraints at point **A** prevent translations in **X**, **Y**, and **Z**, but do not preclude rotations about **A**. The additional constraints at **B** prevent rotations about **Z** and **Y**, and the constraint at **C** prevents rotations about **X**. If the mounted object were to change its dimensions, due to differential thermal contraction with the base, or small machining errors, for example, point **A** would remain fixed, and points **B** and **C**

would move freely towards or away from **A** along their unconstrained directions. It is this allowed free motion which is the key to making a mount kinematic. If another constraint were added, for example an additional X-direction constraint at **B**, then the distance between points **A** and **B** would be fixed, and a dimension change in the object would produce a stress.

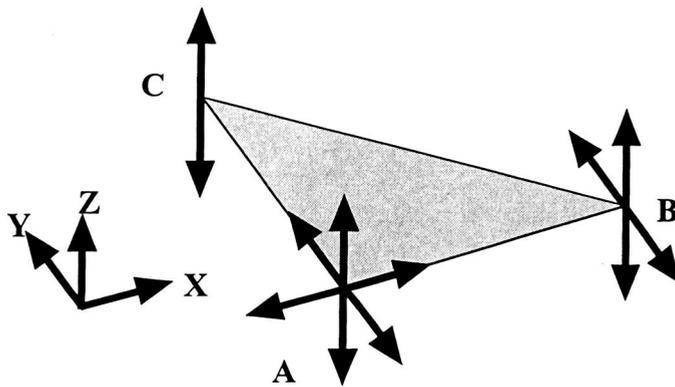


Figure. 4: A 3-2-1 kinematic mount. Arrows indicate directions of constraints attached at A, B and C. Notice that no constraints point towards each other.

A different type of mount, the 2-2-2 kinematic mount, is shown in Figure 5. The analysis is not as obvious as for the 3-2-1 mount, but it will yield to scrutiny. The angles between the three constrained directions in the X-Y plane are typically chosen to be 120° , for symmetry, but they don't need to be, as will be discussed below. The important thing is that the normals to those constraints intersect in a single point, otherwise a uniform dimensional change in the mounted object will result in a rotation.

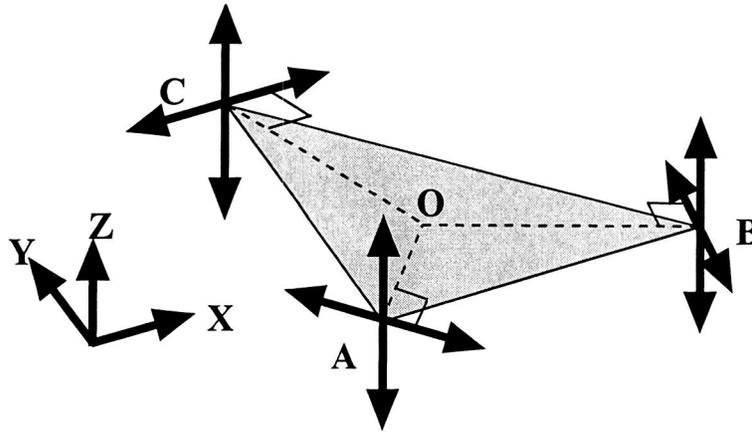


Figure. 5: A 2-2-2 kinematic mount. The constraints at A, B and C which lie in the plane have normals which intersect at point O.

Referring to Figure 5, the two constraints at C prevent the mounted object from translating in X or Z. The addition of the Z-direction constraints at A and B prevents rotations about X and Y. The way this mount constrains Y translations is more subtle: the Y-components of the (X-Y plane) constraints at A and B add up to constrain it. The stiffness of a 1 DOC mount falls off as \cos^2 of the angle one pulls on it with. In the symmetric 120° - 120° - 120° mount presented here, the angle between both of the X-Y plane constraints (at A and B) and the Y axis is 30° , so the perceived lateral stiffness of the mount in Y is $(2) \times (.75) = 1.5$ times the on-axis stiffness of an individual mount. In the X-direction, the angle is 60° , so the contribution of the mounts at A and B is $(2) \times (.25) = .5$. Add to this the stiffness of the mount at C, which is also resisting in X, and one gets the same result of 1.5 times the on-axis stiffness of an individual mount, so the X-Y plane

stiffness of the 2-2-2 kinematic mount is symmetric. Sometimes, the angles between the 2-DOC mounts are chosen to be something other than 120° , for packaging reasons, for example. This is fine, as long as the normals to the constraint directions intersect at a point. The symmetry in the stiffness will be sacrificed. This cannot be taken too far, however: if the angles are changed so that two of the X-Y plane DOCs come close to parallel, the constraints become redundant. A DOF of the system then starts to become unconstrained, and the natural frequency in that mode goes down.

3. The HAWC and SAFIRE ADR suspension system

The HAWC and SAFIRE ADR kinematic suspension system (Figure 6) consists of 2 parts: the top end and the bottom end. The top end constrains translation in X, Y and Z as well as rotation about the axis of the salt pill, but it allows the salt pill to rotate like a pendulum about the other two axes. The bottom end constrains these two rotations by not letting the end of the salt pill move transversely. In this fashion, every motion of the salt pill is uniquely constrained.

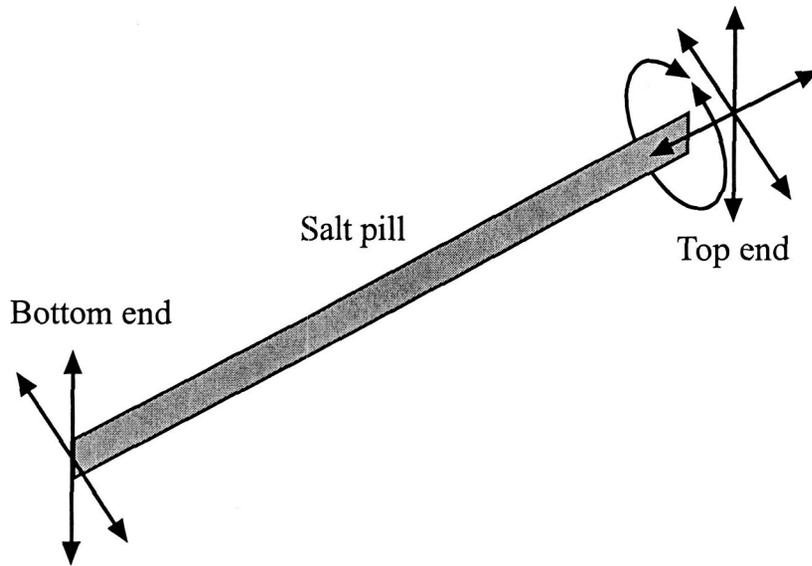


Figure. 6: The schematic configuration of the HAWC and SAFIRE ADR salt pill suspension system. The arrows indicate the directions of the constraints.

The entire assembly is designed to drop into the bore of the electromagnet, which closes out the top end of the helium tank (Figure 7). The bottom of the ADR cavity has a spindle which mates with a ring in the bottom end suspension and provides mechanical support for it. The walls of this cavity are therefore a critical part of the structure of the ADR.

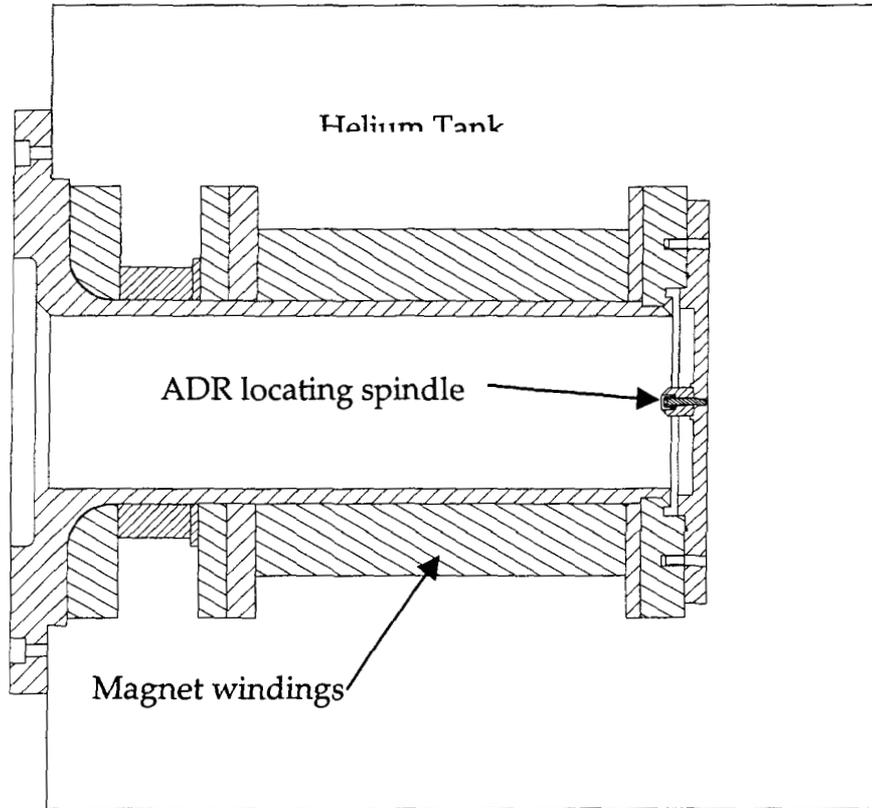


Figure 7: Bore of the electromagnet mounted in the helium tank which the ADR drops into. A spindle at the bottom of the cavity mates with a hole in the bottom end, locating it in X and Y.

3.1 The top end

The design of the top end suspension system borrows heavily from Cui [4] and McCammon [5]. Figures 8, 9, and 10 show the general configuration, and Figure 11 shows a schematic diagram.

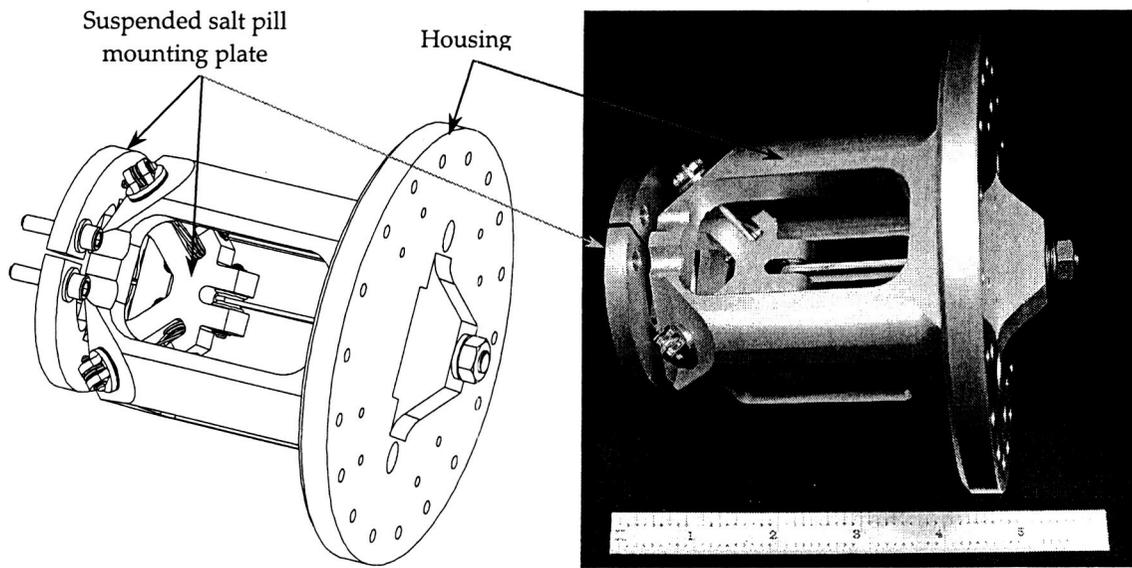


Figure 8: The suspension system top end.

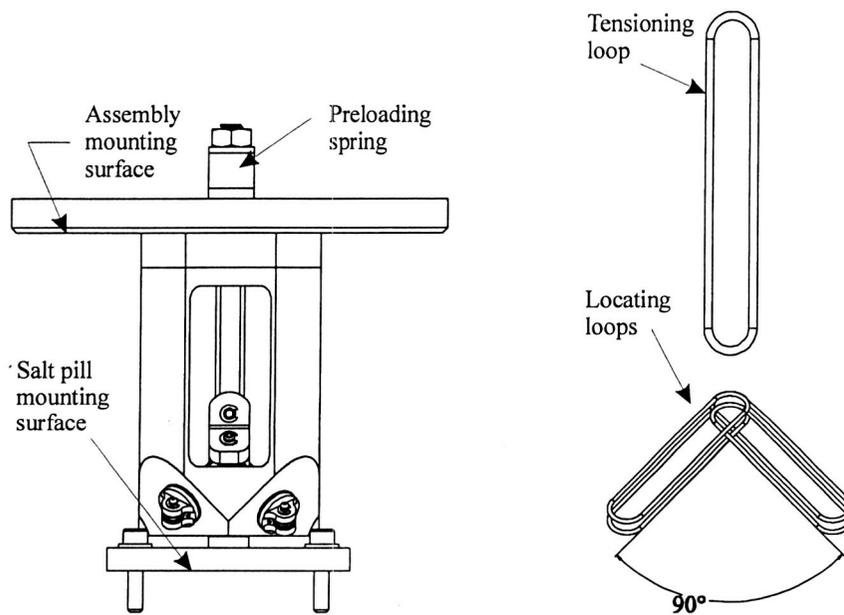


Figure 9: Suspension system top end viewed from the side (left), and the same view with the housing removed, showing the Kevlar loop arrangement (right).

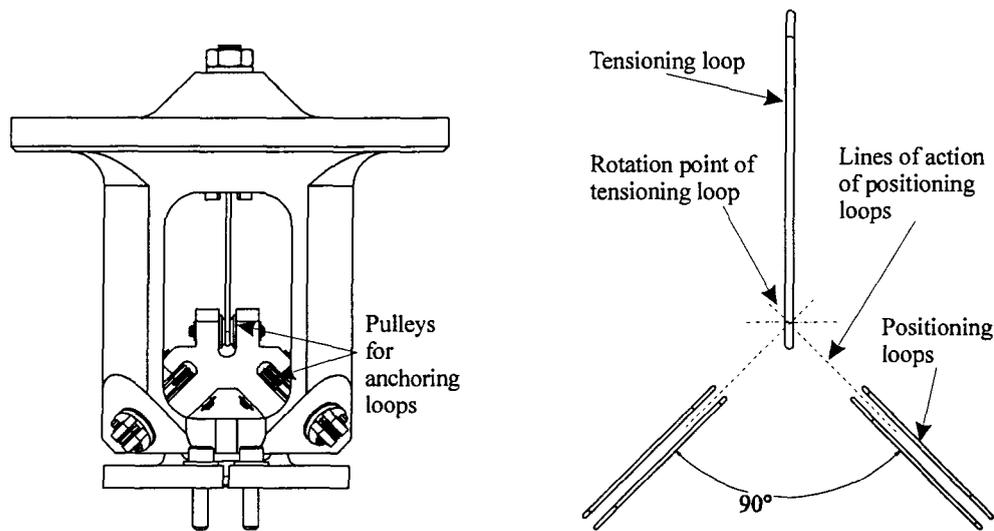


Figure 10: Suspension system top end viewed from the front (left), and with the housing removed (right). The lines of action of the positioning loops intersect at the tensioning loop's rotation axis (normal to the page in this view), yielding an intrinsically stable configuration.

The tensile elements are made from Kevlar which is formed into loops that are fitted around pulleys (Figure 10). To make a loop, a length of unbraided Kevlar fibers is first spliced into a larger loop using Stycast epoxy. The loop is then twisted into a figure-8 and folded back on itself several times, creating a smaller loop where only a fraction of the fibers have a splice.

There are four tensile loops which locate the salt pill mounting surface, and one loop which tensions them all (Figure 11). The positioning loops are rigidly mounted on both ends, and the tensioning loop has a tensioning spring on one end.

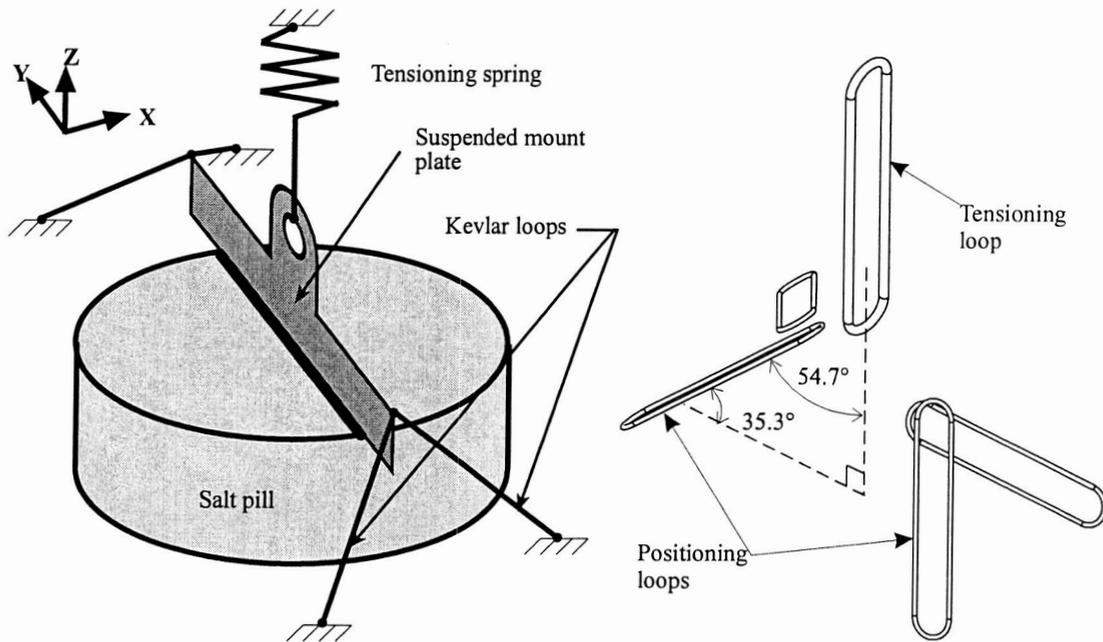


Figure. 11: A schematic of the top end suspension (left), and a similar view of the Kevlar straps with the housing removed (right). The tensioning spring only serves to keep the four locating straps preloaded. The salt pill is free to rotate about X and Y , but is constrained from translating in X, Y, and Z, and from rotating about Z.

When Z axis loads are applied, the four locating loops share the load equally. The angles between the loops are chosen so that the projections onto either the X-Z or Y-Z planes are always 90°. The angle that the loops make with the Z axis is therefore 54.7° (Figure. 6). The perceived stiffness of one loop is $\cos^2(54.7^\circ) = .33$ times the on-axis stiffness of the loop. As there are 4 loops sharing the Z axis load, the stiffness is 1.34 times the on-axis stiffness of one loop.

Recalling that the loops behave as stiffly in compression as they do in tension, as long as their preload is not exceeded, the analysis for X axis and Y axis loading is identical. Therefore, this arrangement yields symmetric X, Y and Z stiffnesses of the top end. The natural frequency of the salt pill in X and Y will be higher than that in Z, because the bottom end suspension will also be resisting translations of the salt pill in those axes.

When seen from above (Figure 12), the projection of the lines of action of opposing locating loops onto the X-Y plane are separated, so the assembly can resist torques. The angle the loops make with the X-Y plane is 35.3° . The perceived stiffness of one loop is then $\cos^2(35.3^\circ) = .67$ times the stiffness of one strap along its axis. The perceived stiffness times the spacing between the projections of the lines of action yields the rotational stiffness

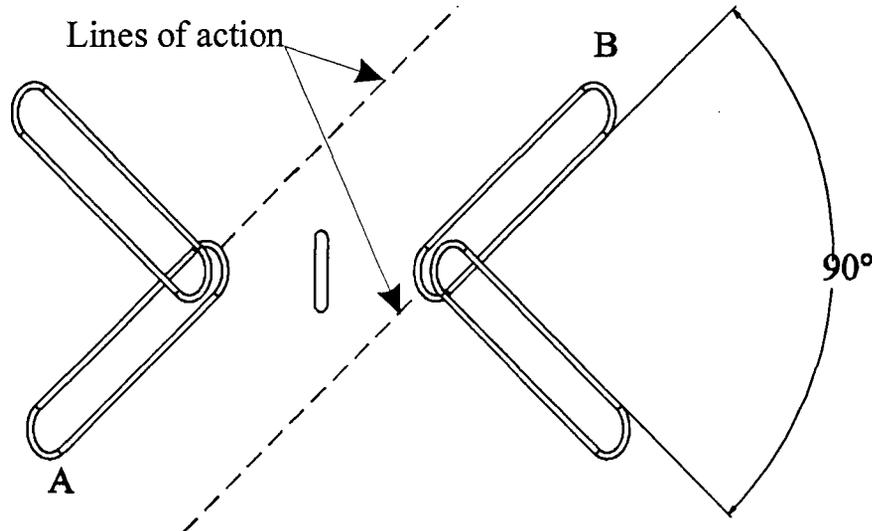


Figure 12: The top end suspension as viewed from above. Since the lines of action of loops A and B do not pass through a point, this arrangement will resist rotations about the salt pill axis. The lines of action of the suspension loops pass through the centers of the supporting dowels.

When viewed from the front (Figure 10), it can be seen that the suspension system might be unstable: if the lines of action of the positioning loops were to intersect at a point above the tensioning loop's rotation point (the point that the tensioning loop pivots around when rotating in the plane of the page for Figure 10, in this case the tangent point of the pulley that the Kevlar is looped around), then a rotation of the suspended mount plate would reduce the tension in all loops, and the configuration would be come apart. Conversely, if the lines of action were to intersect too far below the rotation point, the restoring torque for a small rotational deflection would be too great, and this required degree of freedom would be lost. The best performance is when the lines of action cross right at the rotation point (exactly where this is depends on the details of the design of the pulley, whether it has a groove for the cord, etc.). Small angular deflections engender no restoring torque, and large deflections can be shown to move the intersection point of the lines of action downward, making the mount intrinsically stable. This is important for being able to tension the top end assembly apart from the rest of the ADR.

3.2 The bottom end

The bottom end suspension system (Figure 13) is a 1-1-1 DOC mount, with the mount points at 120° intervals. The analysis is the same as that for a 2-2-2 kinematic mount (Figure 5), except there are no Z-axis constraints. Three 1-DOC tensile mounts (Figure 3) are used. The Kevlar used here is woven cord. The rigid end of the cord is wrapped around a capstan. The cord then passes around a pulley and terminates in a loop, which is made by passing the free end of the cord back into the weave. Cortland Cable [6] provides the cords with the loops already in place. A dowel rod connects this loop to a yoke, which passes the preload to the cord from the tensioning spring. The preload tension is adjusted with a nut. For assembly, the suspended spider is held in the correct position with a jig and then glued to the three tensioned cords using Stycast, to keep residual stresses to a minimum. X and Y translations are resisted by tensions along the length of the cord, but Z translations, and X and Y rotations, are relatively unconstrained. The bottom end mount would provide a constraint to Z-axis rotation, which would conflict with the similar constraint at the top end, except that where the suspended spider engages the spindle in the bottom of the ADR cavity, it is free to rotate. This yields only the desired two degrees of constraint illustrated in Figure 6. To prevent rattling at this joint, the hole in the aluminum spider is made with a very close fit to the titanium spindle. When the

instrument is cooled, differential contraction causes the spider to clamp down on the spindle, after it has found its rotational neutral position, and a rigid joint is formed. Chamfers on the hole and the spindle ensure that, during insertion, the spindle mates with the hole even at the maximum misalignment allowed by the ADR cavity.

ADR cavity.

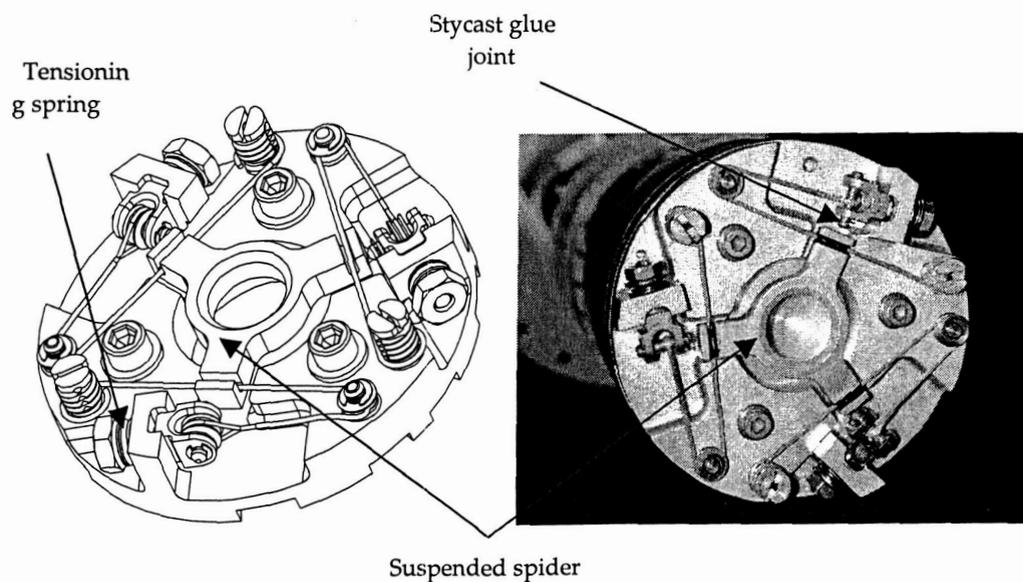


Figure 13: The bottom end suspension.

4. Cryogenic testing

Since the thermal conductance of suspension components can be a significant factor in the design and operation of an ADR, one goal of cryogenic testing was to measure the parasitic heat flow through the suspension system, and compare

this to estimates based on the thermal conductivity of Kevlar [7,8].

Unfortunately, it is difficult to directly measure the conductance of such highly insulating structures because of their long cooldown and equilibration times. The strategy employed here was to carefully measure the thermal conductance of the heat switch in the open state, and then measure the total heat flow between the helium bath and salt pill while the ADR was operational. When the heat switch's conduction is subtracted from the total, the remainder is the combined heat load of the suspension system and other sources such as radiation and instrumentation wiring. Of these, radiation is by far the most significant term. By taking measurements over a range of bath temperatures, its contribution, and hence that of the suspension components, can be isolated.

In the course of the analysis, it became clear that a fraction of the radiative load, approximately $0.3 \mu\text{W}$, was not dependent on bath temperature. Its source is most likely sneak paths for 77K radiation. With this amount subtracted from the radiative load, Table 1, gives the relevant parameters for the HAWC and SAFIRE ADRs. The conducted loads for the suspension system are within 5% of the values calculated for Kevlar based on the lengths and nominal fiber counts and sizes supplied by DuPont.

	SAFIRE ADR	HAWC ADR
Operating temperature	0.100 K	0.200 K
Heat sink temperature	1.27 K	4.25 K
Magnetic field (central field)	2 T	4.5 T
Mass of FAA refrigerant	920 g	920 g
Total parasitic load	2.0 μ W	18.5 μ W
Heat switch parasitic load	1.50 μ W	10.3 μ W

Table 1: SAFIRE and HAWC ADR parameters.

5. Advantages of this system

In summary, the key attributes and advantages of the kinematic suspension system presented here are:

-A *Kevlar* tensile structure provides excellent thermal isolation, and a rigid mechanical mount.

-A *kinematic* mount ensures that there are no overconstrained elements in the system: there are no built-in stresses and the structural analysis is straightforward.

-The load is applied *in-line* with the fibers. A unit deflection of the suspended portion stretches the fibers a unit amount. This approach makes the most efficient use of the Kevlar stiffness.

-The salt pill is not under any stresses except for its own weight- all of the Kevlar cord *preload forces are internal* to the suspension system structure. Therefore, the salt pill container can be lighter and can be optimized for thermal performance. Also, the loads applied to the suspended pill do not change as the temperature varies. These features would be equally useful for mounting optical benches or any other stress-sensitive items.

-The top and bottom end suspension assemblies are built, tensioned and tested *offline*, and bolted to the salt pill as modular units. Four screws for the top end, and three screws for the bottom are all that need to be removed to disassemble the entire suspension, should that be required. This also minimizes handling of the salt pill.

-Both suspension assemblies are *intrinsically stable* even when not mounted inside the magnet bore, so they are easy to handle and tension offline. The stable assemblies and the chamfers on the mating spindle and spider ensure that insertion into the magnet bore is straightforward as well.

6. Acknowledgements

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6. References

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